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Using Lean Techniques and Simulation to Improve the Efficiency of Engineered Wood Production: A Case Study in a Small Factory

Marzieh Ghiyasinasab1*, Lehoux N1, Ménard S2 and Cloutier C1

¹Department of Mechanical Engineering, Laval University, Québec, Canada

²Department of Applied Sciences, Civil Engineering, University of Québec at Chicoutimi, Saguenay, Canada

Abstract

Purpose: Modular construction manufacturing (MCM) has been recognized as an efficient solution to improve standardization and increase efficiency in the construction industry. Production of engineered wood for construction projects may be considered as a type of MCM. The production system of design-specific engineered wood contains some repeatable production processes while each project contains its unique design and specifications. Glued laminated timber (glulam) is a type of engineered wood product which is applicable to construction as an environment-friendly product. Production of curved glulam generally has longer production time than the straight glulam beam. This paper considers improvements in the production of glulam by investigating the sources of waste in the production processes.

Design/methodology/approach: A simulation model is built for glulam production and validated with a case-study for a gridshell project in a small and medium-sized enterprise (SME). Sources of waste are identified, lean methods are suggested for improvement and lean solutions are tested in the simulation model.

Findings and originality/value: The results demonstrate improvements in cycle time and wait time. Since complete elimination of waste may be costly and difficult for an SME when beginning to implement lean techniques, the impact of applying only 50% elimination of non-value adding activities is compared with 100% elimination.

Keywords: Lean approach; Simulation; Cycle time; Construction industry; Engineered wood production

Introduction

Lean manufacturing techniques gained great attention when the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology (MIT) published its findings in 1988 [1]. Since then, lean theory has been adopted widely in manufacturing industries [2]. Following manufacturers, the construction industry also implemented and adopted lean concepts to reduce wastes and increase efficiency [3-5]. However, productivity in the construction industry has improved more slowly than in the manufacturing sector. According to the McKinsey Global Institute report [6], global labor-productivity in construction has grown by only one percent per year over the past two decades, in contrast to a growth of 2.8 percent for the worldwide economy and 3.6 percent in manufacturing. The report suggests that a drastic increase in productivity would be possible if construction was to tend towards a manufacturing-like system with a much higher degree of standardization and modularization and a greater share of off-site production instead of on-site construction.

In this regard, making improvements in the production of prefabricated parts such as engineered wood could help increase efficiency in the construction industry. Prefabricated engineered wood products can be used in residential and non-residential construction projects. They can also be used for many types of structures because of their physical properties and aesthetic appearance [7]. Structural glulam is one of the oldest engineered wood products and is still very competitive in modern construction. Glulam is fabricated from wood boards which are glued together, and they form a beam cross-section of the desired shape [8].

This paper focuses on the glulam manufacturing process and investigates how lean concepts could improve its production efficiency. For this purpose, a simulation model of the glulam manufacturing process was developed, in order to analyze the system, identify possible improvements based on lean concepts, and test different improvement scenarios. More precisely, a general simulation model for the prefabrication of glulam components was first built, based on the production process of a small and medium-sized enterprise (SME) active in the architectural design of buildings, the production of glulam components, and on-site installations. The model was next adapted to simulate the production of curved glulam components required for a gridshell structure project. Then the seven sources of waste in the production process were analyzed and prioritized, according to lean principles. Elimination of three of the more significant sources were targeted (non-value adding activities, transportation, and defects). Lean tools such as single minute exchange of dies (SMED), U-shaped layout, total productive maintenance (TPM), and design for manufacturing and assembly (DFMA) were suggested as improvements and tested with the simulation. Lean solutions were considered both at the ideal level and at a more feasible level. The impact of completely eliminating non-value adding (NVA) activities (100%) versus partial reduction (50%) was analyzed and compared.

Previous studies which followed a simulation methodology were applied to a variety of production systems, however, to our knowledge, glulam production has not been considered in this type of study. The primary contribution of this research is providing a simulation model for glulam production in SMEs which can be adapted to

*Corresponding author: Marzieh Ghiyasinasab, Department of Mechanical Engineering, Laval University, Quebec (QC) Canada, Tel: 4189518464; E-mail: Marzieh.ghiyasinasab.1@ulaval.ca

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different cases. Simulation results provide a decision-making tool for the managers who can preview the impacts of the proposed changes. Developing a step by step approach that starts from feasible and less expensive improvements could motivate the managers to implement a lean approach. Another contribution concerns the identification and prioritization of sources of waste in the production of prefabricated parts for construction, considering the specific characteristics of this system.

In the following sections, a literature review encompassing lean concepts and the simulation approach is presented. The methodology is then described, and a simulation model of glulam production is introduced. Subsequently, the case study and the adopted model are described. The results and a discussion are finally presented, followed by managerial insights and conclusions.

Literature Review

Lean manufacturing practices aim to reduce all forms of waste and inefficiency from production flow towards achieving efficient and flexible systems [1]. Implementation of lean techniques in the construction industry, which is called lean construction, did not grow as quickly as lean manufacturing. The reason being that construction is done on-site and that each project is constructed in a different location [9]. Koskela [10] states that lean construction shares the goals of lean production: elimination of waste, cycle time reduction, and variability reduction. One of the top priorities in the lean approach is the elimination of waste and the activities which consume the time of workers and other resources, without generating value for the final product. These kinds of activities are called non-value adding (NVA) activities in terms of the lean thinking theory [4]. Taylor et al. [11] provided a taxonomy of the different aspects of lean and the tools applied in the industry such as TPM, set up time reduction and kaizen.

Computer simulation provides an excellent environment to implement the principles of lean production [12,13]. Computer simulation is defined as the process of making a mathematically and logically explained model of a real-world system [3]. Simulation can be used for analyzing dynamic systems even where there is uncertainty, and the initial model can be used to test different scenarios for improvement.

The literature contains research on using simulation for implementing lean in a variety of sectors and industries. Although most of the cases are in mass production and large-sized companies, some research shows how the lean approach can be applied in SMEs [14,15], job-shops [16] or in the process industry [17]. Chen et al. [18] studied implementation of a lean system in a small manufacturing company. They identified the production processes and created a current value stream map as well as a future map which served as a goal for future lean activities. They used the 5 whys method to identify the root cause for major bottlenecks and suggested kaizen events to improve the efficiency. Mahfouz et al. [14] developed a simulation-based optimization model to improve lean parameters in a packaging manufacturing SME. They measured three key performance factors: cycle time, WIP (work in process), and workforce utilization, after applying lean tools such as facility layout and preventive maintenance.

Faisal [15] examined the implementation of lean manufacturing using value stream mapping (VSM) for SMEs in the leather industry. Implementing the pull system showed improvements in the average throughput and decrease in WIP. Li [16] carried out a simulation experiment to compare the effects of applying the just-in-time concept to the performances of push and pull systems. Abdulmalek and Rajgopal [17] adapted lean principles for the process sector using VSM and built a simulation model to illustrate potential benefits of reducing lead-time and WIP. They followed lean methods such as the pull system, setup reduction, and total productive maintenance (TPM).

Parthanadee and Buddhakulsomsiri [19] used VSM and simulation to improve the efficiency of the batch production system commonly found in SMEs. VSM was used to identify the problems and find solutions, and simulation was used to analyze the result of applying improvement suggestions. Schmidtke et al. [20] proposed an enhanced VSM method combined with simulation for complex production systems and applied it to the case of exhaust gas purification catalysts production. Abedi Saidabad and Taghizadeh [13] evaluated the function of production lines through computer simulation and made improvements using production line principles such as concurrency of the operations and the least distance. The results showed improvements in waiting time, cycle time, and efficiency for a case study in an iron foundry.

Tokola et al. [2] studied lean manufacturing methods and how simulation is used to consider them. They analyzed 24 articles which addressed lean and manufacturing together. Of these, 46% used VSM to analyze the system and extract NVA activities. Kanban (38%), layout (29%), pull (25%), and WIP (25%) were the other main tools applied. The effects of takt time (21%) and SMED (17%) seemed easy to model as well. Reductions in WIP, lead time, labor, and floor space were frequent results in the simulations. Nagi et al. [21] used a pull simulation model in a multiproduct assembly line. They applied line balancing and workin-process controlling while developing a design of experiments (DOE) method to be tested by the simulation model. The result showed 14% improvement in throughput rate. Zarrin and Azadeh [22] simulated a manufacturing organization with maintenance strategy to evaluate the impact of resilience engineering principles on lean practices. The results showed that redundancy among the resilience engineering principles has the most impact on system performance.

As for lean construction, Farrar et al. [3] presented a systematic approach for the application of lean theory in computer simulation models and implemented it for a case of road construction. The improvements in hourly production rate, resource utilization, and project duration resulted through the elimination of NVA activities and from the implementation of a methodology of pulling material through the process. Nikakhtar et al. [4] demonstrated improvements in cycle time and process efficiency by using multi-skilled teams and sensitivity analysis with simulation for the concrete pouring process. Abbasian-Hosseini et al. [5] applied lean and simulation to determine the best combination of resources in a case study for the bricklaying process. Identifying NVA activities and following lean methods such as justin-time (JIT) and the use of a pull system led to a 40% improvement in productivity.

Yu et al. [23] and Moghadam [24] worked on applying simulation for lean based improvements in manufacturing for modular construction. Ritter et al. [25] mentioned that considerable effort is needed for production line flow balancing because of a large amount of variation and customization in the home construction industry. They used simulation to evaluate the state of production in a case study and analyzed the result of improvements such as labor reallocation which showed an increase in production rate. In a recent research, Opacic *et al.* [7] simulated an engineered wood production system using Any Logic software. They analyzed the system and tested scenarios of different combinations of workers to improve

the production processes based on system analysis. The studied mill produces engineered wood as a final product and sells it to the customers.

Identifying the seven sources of waste and finding solutions to eliminate them are the main elements considered when implementing lean manufacturing. However, the priority and importance of the sources of waste, and how to eliminate them, are different based on the nature of each industry. Therefore, the seven sources of waste specifically related to the production of prefabricated parts for construction are described in this paper. It investigates, through simulation, the implementation of lean concepts for the production of prefabricated parts for construction which shares the characteristics of both manufacturing and construction industries.

Methodology and Simulation Model

With the aim of investigating the impact of implementing the lean approach in the production process for prefabricated glulam components by using the simulation of a case study, this research follows a methodology comparable to the other studies that use a combination of simulation and lean concept implementation. The first and second steps included data gathering and analyzing the glulam production process. A general simulation model was next built based on this production system. It was developed step by step to ensure its verification process. The general model was then adapted for a case study involving the production of glulam components for a gridshell construction project in an SME. Validation of the model was tested by looking at the results with the expert employees from the SME and via a statistical hypothesis test. After ensuring the validation, seven sources of waste in the production process were identified and solutions based on the lean approach were suggested. The suggestions (eliminating NVA activities, transportation and defects) were then tested as distinct scenarios to compare the results. Elimination of NVA activities (overprocessing) was implemented in scenario 1, while partial elimination of NVA activities was tested with scenario 2. The results regarding the cycle time and the wait time were analyzed and compared in as-is, scenario 1, and scenario 2. Elimination of transportation and defects were tested respectively in scenario 3 and scenario 4. In the next step, all improvements were applied to analyze the result of implementing several lean tools simultaneously. Scenario 5 was created to combine complete elimination of NVA activities, elimination of transportation, and elimination of defects simultaneously. As well, scenario 6 was created, mixing partial elimination of NVA activities, elimination of transportation, and elimination of defects. The results of the as-is simulation model with scenario 5 and scenario 6 were analyzed and compared. Then, conclusions and managerial insights were extracted, and the results were presented to the company's manager. Figure 1 summarizes the steps of the research methodology.

Creation of the simulation model for glulam production

To create the simulation model, the general production process of glulam was extracted from the literature and data was gathered from an SME in the Province of Quebec, Canada. A typical glulam manufacturing process consists of lumber drying (when purchasing green lumber), grading, trimming, finger jointing or end jointing, planing, face bonding, finishing, and fabrication [26]. Since most suppliers provide dried wood, there is usually no need for drying in small factories. Purchased laths of wood are inspected to check for the humidity level, elasticity, visual defects, and knots. According to the quality level, wood layers are graded in different degrees such as B, C, and D where B is the best quality level. One of the advantages of glulam



is the possibility of combining the lower qualities of lumber with the higher quality ones. The method consists of placing high-quality laminations on the outer parts of the cross-section where stresses are highest normally, and lower quality laminations in the inner zones to make combined glulam [8]. Figure 2 illustrates typical production processes for glulam.

The simulation model was developed in Arena 15. Basic and advanced process modules in ARENA such as process, decide, batch, separate, assign, and hold were implemented to model the glulam production processes. The process time of most of the process modules followed a triangular distribution. The triangular distribution is commonly used in situations in which the exact form of the distribution is not known, but estimates of the minimum, maximum, and most likely values are available [27]. Process time of pressing was assumed as a constant distribution based on the pressing and curing time needed. In the simulation model, the arrival of raw material was simulated based on the daily work schedule in the SME. Arriving wood is the main entity and the dimensions and degrees were assigned to it using an assign module. The batch module was used to make a glulam beam obtained by gluing layers together. Read and write modules were used to read the information concerning the size and number of layers for each beam. Advanced transfer modules in ARENA such as station and transport were applied to simulate the transportation of material and distances between the stations. In the production process, adhesives such as glue have to be added to the wood laths to make a finger joint. Laths are next planed to obtain a smooth surface and then glued and pressed together to make a beam. The beam must finally be planed as

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well. In the simulation model, planing of the laths after drying process is named planing 1 and planing of the beams after the press is named planing 2. Figure 3 illustrates the main processes and modules of the simulation model.

Verification of the model

Model verification can be briefly described as building the model correctly. In order to avoid errors and problems, it is important to start with a simpler model and improve it gradually. This means breaking up the complete model into a simpler and smaller model and then adding more details to it, which is easier to debug. In programming, this method is called the divide-and-conquer approach. In each step, the model is run, and errors and syntaxes are checked, then more details are added in the next step [28]. After building the model, some tools and modules were used to visualize and check how the model works. These tools include: using different entity pictures for different types of entities, following entities, changing entity pictures, changing resource pictures, displaying values and plots, and writing to an output file.

Case Study

Adapting the simulation model to reflect the case study

The production of glulam for a particular construction project was observed and, based on the data gathered, the simulation model was modified to better reflect this reality. The construction project was a gridshell structure and all components were curved beams. Timber gridshells are free-formed structures which are defined as structures "with the shape and strength of a double curvature shell but made of a grid instead of a solid surface" [29].

The SME responsible for producing this type of structure encompasses about thirty employees and one glulam production line. Three different shapes of glulam are manufactured in this factory: straight beams, round beams, and curved beams (arcs). Production processes for straight and curved glulam beams are the same. The difference comes from the set-up time for the press machine. For the straight beams, once the press machine is set, the same set-up can be used for all beams. While for the curved beams, the set-up must be changed for different radiuses. This difference makes the production of curved glulam more complicated and longer than straight beams.

The glulam production method in this factory is generally comparable to the standard glulam production process. However, there are differences based on the type of machinery, the level of optimization, and the capacity of the factory. As a result, the production of a gridshell structure was investigated and process times extracted. Based on the available data, the simulated process times were defined as distributions, listed in Table 1.

Information from the factory such as machinery and human resources needed for each process, distances between stations, the failure rate of the equipment, and working time schedule, etc. were also added to the model. The same divide-and-conquer approach was applied to ensure the verification of the model. Figure 4 shows a screenshot picture of the simulation model for a gridshell project.

Validation of the model

Because of the random nature of a simulation model, a single run of the model is not sufficient [27]. Kelton et al. [27] suggests running the model with an initial number of runs and to then verify if the confidence interval is acceptable. Based on Kelton et al.'s work, a formula was used by researchers such as Nikakhtar et al. [4] and Toledo et al. [30] to identify the adequate number of runs. The formula

is:
$$N(m) = \left[\frac{s(m)t_{m-1,1-\frac{\alpha}{2}}}{\overline{X}(m)\varepsilon}\right]^2$$
, where N(m) is the required number of

simulation runs, m is the chosen number of replications, $\overline{X}(m)$ is the sample mean from m replications and is the estimate of the real mean μ , S(m) is the standard deviation from m simulation runs, α is the level of significance (considered 95%), ε is an allowance for error.

Process	Distribution	Distribution parameters (minutes)
Inspection	Triangular	a=22, m=25, b=28 (a: min, m: mode, b : max)
Finger joint	Triangular	a=1.1, m=1.5, b=2
Drying	Triangular	a=12, m=13, b=14
Planing 1	Triangular	a=5, m=6, b=7
Pile up	Triangular	a=12, m=15, b=18
Gluing	Triangular	a=30, m=35, b=40
Cold Press	Constant	Value : 150
Planing 2	Triangular	a=21, m=24, b=27
Carpentry 1	Triangular	a=120, m=126, b=132
Carpentry 2	Triangular	a=120, m=126, b=132
Carpentry 3	Triangular	a=120, m=126, b=132
Finishing 1	Triangular	a=36, m=41, b=46
Finishing 2	Triangular	a=36, m=41, b=46

Table 1: Process distribution parameters of glulam production.

And ______ is the upper $1-\alpha/2$ critical point from the Student's t distribution with m-1 degrees of freedom. The initial 10 number of runs were tested and the mean and standard deviation for the production time was calculated. The results showed: $\overline{X}(10) = 178$ and S(10) = 11.09. Based on the previous formula and considering 95% level of confidence, t9,0.025=2.262 and ε =0.05, the number of runs should be more than 8 to obtain reliable results. Therefore, 10 runs are considered as sufficient for the simulation iterations.

One of the validation methods is comparing the simulation model output behavior to the system output behavior [31]. The results were observed, and the average cycle time was compared with the cycle time for the real gridshell project. The comparison is shown in Table 2 (times are in hours).

Process	Real cycle time	Simulated cycle time	Difference	
Production	168	178	5.95%	
Carpentry	168.5	157.44	6.5%	

Table 2: Comparing simulation time with real cycle time.

To confirm the validity of the model, face validity was considered by asking the knowledgeable individuals who know the system [31]. The simulation model was presented to the employees from the factory and they confirmed that it represented the real operations faithfully. Moreover, a statistical test was used to ensure the validity. A hypothesis test for the mean of the normal distribution with unknown variance was applied by using the student's t-test.

The average project duration for 10 replications was 168 hours with a standard deviation of 14.28 hours. The hypotheses for this test were $H_0: \overline{X} = \mu = 168 \ hours$ and $H_1: \overline{X} \neq \mu$. The significance level $\alpha = 0.05$ and the number of replications n=10. With the student distribution, $t_{\left(1-\frac{\alpha}{2};n-1\right)} = t_{\left(0.025;9\right)} = 2.262$. The statistical value

$$t_0 = \frac{\overline{X} - \mu_0}{S / \sqrt{n}} = \frac{178 - 168}{14.28 / \sqrt{10}} = 2.21 |t_0| = 2.21 \neq |t| = 2.262 \text{ , then } H_0 \text{ could}$$

not be rejected and the model was accepted as being valid.

Results

One of the top priorities in the lean approach is the elimination of waste. Seven types of waste are defined by lean thinking: overproduction, unnecessary inventory, unnecessary motion, waiting, inappropriate processing, excessive transportation, and defects [4]. In the following subsections (5.1 to 5.7), the sources of these seven wastes were extracted from the case study. Lean methods were proposed to reduce three of these wastes, including NVA processes, transportation, and defects, while the impacts of these methods were analyzed using simulation.

Overproduction

Overproduction is not a major problem in this industry since production is always based on the customer's request.

Inventory

Storage of raw material, final or intermediate products in the production line, slows down the production. Generally, in glulam production, process time varies in different stations. Since a certain number of layers must be prepared and then glued together, some storage is inevitable. Production levelling should be considered which

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is not within the scope of this research. In this study, the focus was on reducing waiting time of materials in the workstations which lead to reducing storage. A detailed explanation is provided in the next sections.

Motion

Motion encompasses excessive movements of operators to use the tools and work with the machinery or to follow production processes. In this case-study, unorganized workplaces and lack of standard work charts were an important source of motion. 5S, visual control, optimization of space, and standardized work charts at each workstation are lean methods that could reduce this motion.

Waiting

In this case, waiting does not add value to the product. Therefore, wait time is considered as a performance factor which should be reduced.

Over-processing (NVA activities)

Overprocessing refers to the activities which do not add value to the product. In this case, inspection and the set-up time for the press were sources of waiting. Pile-up of laths was another process that did not add value to the product. These three processes and the suggestion to eliminate them are discussed in the following.

Inspection: In this case study, one operator is assigned to the inspection process and does most of the work by visual inspection using a Mechanical Timber Grader (MTG). Reducing the inspection time to a minimum would reduce costs and delays as well as the risk of stopping the production line because the wood is waiting for inspection. There are three possibilities to reduce the inspection time.

• Purchasing an automatic wood scanner which costs between

\$400,000 and \$800,000 (X-Ray model);

- Recruitment of another operator;
- Getting help from the current production staff.

The price of the inspection machine is not currently affordable for the company, therefore the feasible solution would be to increase the human resources. To investigate this change, the inspection module was first removed and the process eliminated in scenario 1. In scenario 2, the inspection time was reduced by 50% by adding another worker.

Press set-up: Another activity that needs to be reduced as much as possible is the press set-up time. The set-up process takes 4 hours each time the machine is used to produce curved beams. For the gridshell project, using only curved beams, set-up time is significant. According to lean production, the set-up time should be less than 10 minutes [32], using the Single Minute Exchange of Die (SMED) method. This objective is not possible for the factory, however, the following steps are suggested to reduce the set-up time from 4 hours to 2 hours.

- 1. Maximize the set-up activities that can be done while the press machine is working (external elements);
- 2. Simplify and streamline all elements;
- 3. Standardize procedures for the workers to follow and limit wasted time;
- 4. Create auxiliary tools and equipment to make the set-up quicker.

The suggested steps can be implemented by analyzing the use of the press machine in collaboration with the machine's manufacturer. In scenario 1, the delay module which simulates the set-up time was removed so as to analyze the result of eliminating set-up time. In

scenario 2 the delay was reduced to 2 hours which represents a 50% reduction in set-up time.

Pile-up: In the production process, there is a station before gluing of the beam where the laths are piled up and an operator decides which combination of wood layers should be glued together. For example, to produce a 5 layer glulam beam, the two top layers must be of grade B, grade C is acceptable for the central layer, and the two bottom layers should be grade B. This process is required because the laths are produced by batches of quality degree instead of based on the glulam beam's needs. This process can be omitted and the operator will be freed if laths are produced using a daily plan based on glulam production needs. As with the two previous NVA activities, in scenario 1, the pileup process was removed and the operator was freed. In scenario 2, the pile-up station was kept while the time was reduced by 50%.

The results of eliminating NVA activities: The lean approach aims to have a system with zero NVA activities and waste. Simulating the proposed methods to eliminate inspection, set-up, and pile up, showed that the cycle time could be reduced from 178 hours to 135 hours which is an improvement of 24%. Wait time would be reduced from 202 hours to 162 hours, a 20% improvement. The result shows noticeable improvements for this one project which suggests more improvements in the long term.

However, it is important to find feasible solutions that respect the real factory's situation. In most cases, inspection is assumed to be a NVA activity [4]. In the production of engineered wood, inspection is an important process to ensure the quality restrictions. Moreover, checking for knots and grading is part of the production process and cannot be eliminated.

Hence, instead of eliminating NVA activities completely, the factory in this case study thought it more realistic to aim for reducing

Front/Exit

door

inspection and set-up times by 50% instead of 100%. In the second scenario, NVA activities were not completely eliminated and their times were rather reduced by 50% to examine the results. The simulated results show that cycle time was reduced from 178 hours to 146 hours (18% improvement instead of 24%) while wait time was reduced from 202 hours to 176 hours (13% improvement instead of 20%). Figure 5 illustrates the results and comparison between as-is, complete NVA elimination (sceanrio 1), and partial NVA elimination (sceanrio 2).

Transportation

As shown in the factory layout in Figure 6, the production flow is not efficient. There is significant unnecessary transportation from the pile-up station to gluing, from the cold press to the planing 2 station, and from the finishing station to the exit door. Eliminating the pile up process and changing the layout to make a U-shaped production line would improve the production flow. Figure 7 illustrates the suggested layout.

To ensure the feasibility of changing the layout, dimensions of the machinery and factory were measured and the accessibility to electricity was examined based on the layout plan. The proposed layout was furthermore validated with the experts in the factory. Then the U-shaped layout was applied in scenario 3 by changing the station modules and their distances and sequences. The results show that the cycle time was reduced from 178 hours to 176 hours which is not a noticeable improvement (1.12%). However, the wait time was reduced from 202 hours to 62 hours (69.53%) which is significant. Reduction in wait time results in a smoother flow of material in the production line. This change could lead to improvements in cycle time in the future.

Defects (failure and rework)

Pile up

Carpentry

Finishing

The last category of waste which is considered in this study relates



Cold Press

Planing 2

Figure 6: Current factory layout with unnecessary transportation.

Gluing

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to defects. Two sources of defects are machinery failure and rework.

Failure: Based on the observations and operators' information, the simulation model represents the failure rate of machinery with a triangular distribution. In the factory, the sudden breakdown of machinery occurs, however, the rate of failure has not been documented. The first step of improvement would be to document failure occurrences and hold regular meetings to analyze the reasons. The second step would be to implement the Total Productive Maintenance (TPM) method. According to Abdulmalek and Rajgopal [17], TPM involves:

- Constantly monitoring machinery breakdown and finding the failure rate;
- Discussions to find the source of the problems;
- Autonomous maintenance;
- Safety and environment management;
- Planned maintenance instead of condition-based maintenance.

According to the factory's work schedule, Tuesday to Friday the press machine is loaded with the layers of laths which were produced the day before. However, since the factory is closed on weekends and planed laths cannot be kept more than 24 hours, the press is idle on Monday morning while laths are being produced. Therefore, Monday morning is an appropriate time for preventive maintenance of the press. For the other equipment, lunchtime is suggested. The proposed times for preventive maintenance is presented in Table 3.

In the simulation model, equipment failure was defined with a triangular distribution and assigned to each machine. For example, for the press machine, failure rate was TRIA (80, 90, 100) with three hours of downtime. This rate means that, on average, after 90 uses, a threehour failure occurs.

Rework: The main amount of rework for the specific project under study (gridshell structure) came from the inconsistencies in design detected at the carpentry station (second-last station). For this gridshell project, large curved glulam beams were built and then cut into smaller parts at the carpentry station. This design created waste in both material and process time. It was also the source of mistakes and rework. In all, the carpentry station realized that 20% of the products needed rework. When the company receives plans from the client's architect, the company must define the specifications for each glulam beam and provide detailed plans for production, carpentry and finishing stations. Using design for manufacturing and assembly (DFMA) methods for this process would be beneficial as they focus on improving the design

Machinery	I	Maintenance	Maintenance schedule		
	Uptime (days)	Downtime (minutes)	-		
Finger joint	7	60	Tuesday:	12 h-13 h	
Drying	7	60	Wednesday:	12 h-13 h	
Planing 1	7	60	Thursday:	12 h-13 h	
Planing 2	7	60	Friday:	12 h-13 h	
Press	7	120	Monday:	8 h-10 h	

Table 3: Proposed preventive maintenance schedule.

phase in order to prevent errors in the final products. According to DFMA, the following steps must be considered:

- Use standard, off-the-shelf parts rather than custom components;
- Design for ease of fabrication;
- Aim for mistake-proof design;
- Design with predetermined assembly technique in mind. •

The elimination of defects was applied in scenario 4 by removing the failure rate and the rework process from the model. Elimination of these wastes in the model showed that cycle time could be reduced from 178 hours to 175.7 hours which is not significant (1.23%), while the wait time was noticeably reduced from 202 hours to 89 hours (56% improvement). Lean concepts aim for the elimination of failure, however total elimination might not be feasible in this case. Nonetheless, with the simulation, this ultimate goal can be tested in order to investigate the possible gains in cycle time and wait time and encourage the company to implement TPM.

Summary

Table 4 summarizes the sources of waste for the case studied, their cause, and the lean tools proposed to reduce them. This list can be considered more generally for similar small companies that produce engineered wood for construction projects.

Discussion

Applying all changes simultaneously

Simulation results when reducing the three targetted sources of waste individually, all show improvements in cycle time and wait time. Scenario 5 was therefore created in order to simulate the implementation of all changes simultaneously. Scenario 5 tests complete elimination of NVA, transportation and failure. The results demonstrate 27% reduction in cycle time (from 178 h to 129 h) and 77% reduction in wait time (from 202 h to 47 h).

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Additionally, the result of more realistic improvements which mean reducing the inspection and set-up times by 50% was investigated by creating scenario 6. The results show that with partial improvements of NVA, together with the elimination of transportation and defects, the cycle time still has 26% improvement (from 178 h to 132 h) and wait time indicates 75% improvement (from 202 h to 50 h). Charts in Figure 8 illustrate the comparison between partial (scenario 6) and complete (scenario 5) implementation of the lean approach. The result is interesting as there is a drastic reduction from the actual production system and partial implementation of a lean approach, while the difference between the partial and complete implementation is much smaller. This result confirms that using lean approaches to even partially reduce wastes can be profitable. For the SME, these first steps could lead to continuous improvement in order to reach higher levels of efficiency in the future. Table 5 summarizes the changes and results for each scenario.

Managerial insights

Seven sources of waste are recognized in lean production and lean construction theory. The importance and role of these sources can vary in different industries. In the contexts of production for construction and mass customization, production is based on the customer's order and inventory and overproduction are typically not the main issues. Therefore, the first step toward lean can focus on the reduction of NVA activities, transportation and defects. Even partial improvements could have a significant impact on efficiency. Improvements that do not require considerable investments seem more easily accepted by managers. However, complete elimination of these wastes should be taken into consideration as a long-term goal. Reduction of motion, inventory and overproduction should also be considered. After these basic steps of implementing lean concepts, and reaching a smooth production flow, other hidden problems may be revealed. Analyzing the production system and finding solutions for improvement should be repeated periodically to achieve continuous improvement as emphasized by the lean approach. The suggested steps are illustrated in Figure 9.

Conclusion

This research considered applying the lean approach in an SME active in the architectural design of buildings and production of glulam components. Firstly, the production of glulam was simulated using Arena software. Then the general simulation model was modified for the case-study under investigation.

Waste	Cause	Lean tools		
Overproduction	Not the main source in this case	-		
Inventory	Not the main source in this case	-		
Motion	Unorganized workplaces Lack of standard work charts	5S, Visual control, Standardized work charts		
Waiting	Due to over-processing, transport, defects	Analysing the value stream		
Over-processing	Inspection	Eliminating NVA processes		
(NVA processes)	Set-up	SMED		
	Pile-up	Eliminating NVA processes		
Transportation	Inefficient layout	U-shaped layout		
Defects	Failure	ТРМ		
	Rework	DFMA		





	Simulation parameters					Results		
	Inspectiontime	Set-up time	Pile-up time	Layout shape	Failure rate	Rework rate	Cycle time (hours)	Wait time (hours)
As-is	Average 25 min	4 hours	Average 15 min	Original	3h per 90 uses	20%	178	202
Scenario 1	0	0	0	Original	3h per 90 uses	20%	135	162
Scenario 2	Average 12.5 min	2 hours	Average 7.5 min	Original	3h per 90 uses	20%	146	176
Scenario 3	Average 25 min	4 hours	Average 15 min	U-Shape	3h per 90 uses	20%	176	62
Scenario 4	Average 25 min	4 hours	Average 15 min	Original	0	0	175.5	89
Scenario 5	0	0	0	U-Shape	0	0	129	47
Scenario 6	Average 12.5 min	2 hours	Average 7.5 min	U-Shape	0	0	132	50

Table 5: Summary of the scenarios and results.



The seven sources of waste were identified, and improvements were suggested based on the lean approach. Three main sources of waste were highlighted as NVA activities, transportation, and defects. NVA activities include inspection, set-up and pile up. Simulating the elimination of these three activities led to a 24% improvement in cycle time and 20% improvement in wait time. However, a more feasible solution such as adding an operator to the inspection process and adapting SMED concepts resulted in a 50% decrease in inspection and set up times. This solution resulted in 18% improvement in cycle time and 13% improvement in wait time. The pile up process could be eliminated by providing a standard action plan. Reducing transportation by changing the factory layout to a U-shaped layout gave 1.12% improvement in cycle time and 69.53% improvement in wait time. The machinery failure rate could be reduced by using a TPM system and rework could be eliminated with DFMA. These improvements led to a 1.23% reduction in cycle time and 56% reduction in wait time. Hence, improvement in NVA activities indicated a higher impact on cycle time, while improvement in transportation and defects showed a higher impact on wait time.

The impact of all improvements together was also considered. The result of eliminating these three sources of waste led to a 27% reduction in cycle time and 77% reduction in wait time. In the case of partial elimination of NVA activities, the results were 26% reduction in cycle time and 75% reduction in wait time, which is very close to the results for the complete elimination of NVA activities. From a managerial point of view, reducing NVA activities, transportation, and defects appeared as the improvement priorities for glulam production in the SME under study. Elimination of all sources of waste could be the next step which follows the concept of continuous improvement to achieve a lean production system.

This research attempts to apply the lean approach in an SME that manufactures glulam. Applying the method is limited to a case study of a gridshell project that represents production of curved glulam for a timber construction project. Studying more samples and considering the production of different projects would provide complementary results to improve the production of engineered wood for the construction industry.

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